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Modelling mean forces and moments due to waves based on RANS simulations

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ABSTRACT

In order to predict manoeuvrability of ships in seaways a mathematical model for approximating the hydrodynamic forces acting on the ship has been extended for taking into account mean forces and moments due to waves. RANS computations for a twin screw passenger ship in waves of various lengths coming from all directions have been used to determine the coefficients of the mathematical model. The paper shows that a double parametric approach on wave length and encountering angle is capable of reconstructing the mean forces and moments for all considered situations.

KEY WORDS: drift forces, RANS, mean wave forces, modelling, ship flow, manoeuvring, oblique waves.

INTRODUCTION

In the past years it has become common practice to use numerical methods for turbulent flows to predict the manoeuvrability of a ship in calm water. The effect of incoming waves thereby is still neglected in most cases. In order to predict manoeuvrability in waves and - in particular - to estimate the minimum power required to maintain a reasonable manoeuvrability in adverse seaway conditions, it is necessary to quantify the mean wave forces and moments acting on the ship during a manoeuvre.

A classical way for predicting rudder manoeuvres in calm water consists in approximating forces and moments due to ship motions and rudder deflection using a mathematical model. This allows solving the set of motion equations of the ship, assumed to be rigid, with a suitable numerical time integration algorithm. In the present work a mathematical model of Abkowitz type (Abkowitz, 1964) is being extended for taking into account mean forces and moments due to waves, in order to predict rudder manoeuvres of the ship sailing in adverse conditions.

The basic mathematical model for calm water, consisting of hydrodynamic coefficients which reflect the influence of motion and steering parameters on the hydrodynamic forces acting on the ship, has proven to perform satisfactorily for several applications as shown by the Stern and Agdup (2008); Cura-Hochbaum et al. (2008); Cura-Hochbaum and Uharek (2014) in the workshops SIMMAN 2008 and 2014 . The coefficients can be determined by means of virtual captive model tests, see Cura-Hochbaum (2006). As a first step towards manoeuvring prediction in moderate long crested seaways, additional terms and corresponding coefficients taking into account the mean effect of the waves are now included to this basic mathematical model.

When taking wave effects into account, two considerably different time scales can be considered. The motion of the ship due to wave forces and moments of first order in the wave amplitude represents the typical seakeeping problem. These forces having usually very large amplitudes but zero mean values cause (relatively) high frequency motions in all six degrees of freedom. For manoeuvring prediction however, it may be a valid assumption that the harmonically oscillating first order forces do not influence the resulting (low frequency) global motions during the manoeuvre, provided that the encountering frequency of the wave does not become too small (Yasukawa and Nakayama, 2009). The only forces and moments to be added to the mathematical model for manoeuvring prediction are thus the non-zero mean values of second (or higher) order forces, also called drift forces.

This extension can be done by a simple approach, where mean wave forces and moments on the ship sailing steadily straight ahead in diverse obliquely incoming individual waves are stored in a database and their values for the current situation are calculated by a multidimensional interpolation from the database information. Another - more elegant - approach is to state a functional relationship between mean forces and all relevant parameters. With the usual assumption that the mean forces and moments due to a single harmonic wave depend quadratically on the wave amplitude ($\hat{\zeta}_w$), the remaining parameters considered for a suitable description of these forces are the wave length (λ) or frequency (ω) and the encountering angle (α). The following procedure is a first attempt to model the wave forces depending only on α and ω. In the final model the dependence on the ship speed (u), which relevance is being investigated at moment, will be modelled as well. Alternatively, a hybrid approach, where several sets of coefficients (just depending on α and λ) for different values of u are stored in a database, could be a good compromise.

To capture the dependencies mentioned above, Reynolds-averaged Navier-Stokes (RANS) simulations for the ship in regular waves are performed. Seakeeping calculations for a ship sailing in regular waves are traditionally performed using strip or panel methods, both based on potential flow theory, since forces and moments due to waves do usually not significantly depend on viscosity. For moderate seaways most interesting motions and loads are predicted well, even if all methods taking the forward speed of the ship into account are linear. Linear methods are per se not able to predict mean wave forces but stratagems have been developed to obtain them from the linear responses of the ship, see for instance Faltinsen (1990). The use of a RANS technique, which implicitly includes not only viscous but also non linear effects, for simulating the flow around the ship sailing in oblique waves avoids the mentioned detour. In order to get a better understanding of diffraction and radiation effects and to allow a reliable comparison with available experimental data, all computations are first performed for the fixed ship condition, i.e. all motions excepting the constant ship speed are suppressed during the RANS simulations.

The RANS computations are performed for various wave lengths, ranging from 0.75 to 1.25 times the ship length L and encountering angles from 0° to 180°. The relatively small wave length of 0.75 L requires a quite high resolution of the computational grid in order to keep numerical diffusion acceptably low. All computations were performed at the same grid.

CALCULATIONS

Numerical code The numerical code used for all computations is Neptuno, an updated version of the nepIII code, which has already proven to perform satisfactorily in many manoeuvring and seakeeping applications, see for instance Cura-Hochbaum and Vogt (2002).

The incompressible RANS equation and continuity equation are solved in a ship fixed coordinate system. All equations have been made nondimensional with respect to a characteristic length and speed and water density.

Pressure and velocities are coupled by means of the SIMPLE algorithm. The turbulence is modelled with the standard k-ω turbulence model of Wilcox (Wilcox, 1993). Neptuno is one of the few codes using a level-set technique for two phase flow (Sussman et al., 1994) in order to calculate the free surface flow around the ship.

All equations are solved on a curvilinear block structured grid using a finite volume approach. The technique allows to have non matching interfaces at adjacent block sides to deal with complicated geometric constraints.

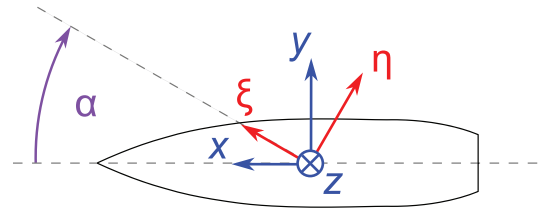

Fig. 1 Coordinate system

Convective terms are discretised using a linear upwind differencing scheme (LUDS), diffusion terms with a central differencing scheme (CDS). Time integration is performed with a second order multilevel implicit method. The code is described in detail in the publications mentioned above (Cura-Hochbaum and Vogt, 2002; Cura-Hochbaum, 2006; Cura-Hochbaum et al., 2008).

Coordinate system The two coordinate systems used in the calculations are one earth fixed system with coordinates ξ, η, ζ and a ship fixed system with coordinates x, y, z, see figure 1. All conservation equations are stated in the ship fixed, non-inertial coordinate system, taking into account the corresponding inertial terms. This has to be considered when setting the boundary conditions.

The waves generated at the inlet boundaries (at the front and starboard side) of the computational domain are defined such that they propagate in negative direction of the earth fixed ξ axis. Since the mathematical model is going to be used for manoeuvring simulation, we define the wave encountering angle α as shown in figure 1. Note that head waves correspond to $\alpha = 0^\circ$ (not $\mu = 180^\circ$ as usual), beam seas from starboard side to $\alpha = 90^\circ$ and following seas to $\alpha = 180^\circ$.

Boundary Conditions The boundary conditions are implemented using ghost cells which provide explicit values at the border updated in every time step.
At the front and starboard side of the computational domain all three velocity components, the values for k and ω and the level set function (free surface elevation) are given. At the rear and port side the hydrostatic pressure distribution is given. The top and bottom boundaries are approximated as free slip walls.

To generate a single harmonic wave in the computational domain, the uniform inflow boundary conditions at the front and starboard side are superposed with the orbital velocity components of the wave and free surface elevation according to the Airy wave theory. The equations in the earth fixed system are as follows:

$$\zeta_w = -\hat{\zeta}_w \cdot \sin(k\xi_b + \omega t) \tag{1}$$

$$u_w = -\omega \cdot \hat{\zeta}_w \cdot \frac{\cosh\left(k(\zeta_b - H)\right)}{\sinh(kH)} \cdot \sin\left(k\xi_b + \omega t\right) \tag{2}$$

$$w_w = \omega \cdot \hat{\zeta}_w \cdot \frac{\sinh\left(k(\zeta_b - H)\right)}{\sinh(kH)} \cdot \cos\left(k\xi_b + \omega t\right) \tag{3}$$

Where $\hat{\zeta}_w$ denotes the wave amplitude, H the water depth, k the wave number, ω the circular frequency of the wave and ξ_b, η_b, ζ_b the position of the considered point of the boundary.

		full scale	model
λ	scale factor	1.0	72.0
L [m]	length	220.27	3.059
B [m]	beam	32.2	0.447
T [m]	draught	7.2	0.1
V [m^3]	displacement	33229	0.089
S [m^2]	wetted area	5975	1.509
v [m/s]	speed	10.8	1.273
Fn	Froude number	0.232	0.232
Re	Reynolds number	2.38 10^9	3.89 10^6

Table 1 Main Particulars

It should be noted that the frequency of the generated wave in a moving domain is not the wave frequency ω, but the encountering frequency ω_e which reads:

$$\omega_e = \omega - k \cdot u \cdot \cos \mu \tag{4}$$

u is the ship speed and μ the usual encountering angle of the wave.

Test ship The procedure described above is being applied to a twin screw passenger ship for which experiments are being performed at the towing tank of TU Berlin and validation data will be available in the near future. The ship was modelled including bilge keels, rudders, propeller shafts and struts, see figure 2. It is sailing at a Froude number of 0.232, which leads to a Reynolds number of 3.9 10^6 at a model scale ratio of 1:72.

The grid For generating the computational grid, the commercial tool ICEM was used. In order to ensure an appropriate resolution of the incoming wave and the wave system of the ship itself a total number of 4 million cells was needed. Note that to simulate quartering and beam seas a high resolution in longitudinal and transversal direction is required. Numerical damping zones have been added at the outlets foreseen for oblique waves, behind and beside the ship on the port side to avoid reflections from the borders into the computational domain, which extends from 0.5 L in front of to 4.5 L behind the ship. The border on the starboard side is located at one L beside the ship, the one on the port side is at 2.8 L. The depth of the domain is one L.

The computations have been performed using wall functions. A target value of 80 was chosen for the non dimensional wall distance parameter y^+ of the first cell layer at the ship hull, as recommended by Wilcox (1993).

In order to check the grid dependence of the solution the grid was systematically refined, leading to a total of 32 Million cells, as well as coarsened to a total number of 500.000 cells.

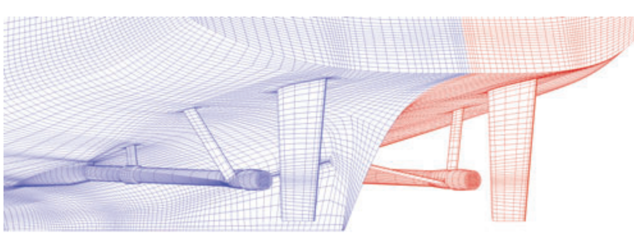

Fig. 2 Grid including appendages

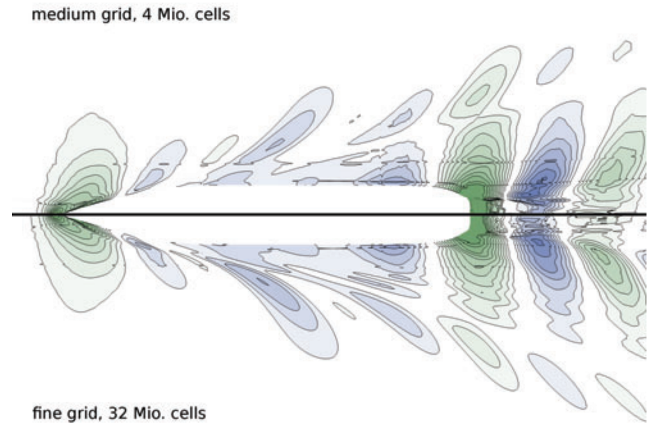

Fig. 3 Free surface elevation in calm water

Calm water In order to calculate the added resistance in waves, the calm water resistance needs to be known. Furthermore the converged calm water solution serves as starting condition for the following computations in waves to speed up the calculation time. The calm water solution was calculated for all three grid refinement levels, allowing a grid dependence analysis.

Figure 3 shows the free surface elevation on the medium and fine grid. As can be seen the medium grid already provides a satisfactory resolution of the free surface elevation. The calm water resistance calculated on the medium grid is 5.79 N, the fine grid yields a resistance of 5.60 N.

In order to validate the CFD computations at first the grid dependence of the solution was investigated. The friction and pressure components of the total resistance for each grid are:

	C_F 10^{-3}	C_P 10^{-3}	C_T 10^{-3}
coarse grid	3.717	0.966	4.683
medium grid	4.085	0.678	4.763
fine grid	4.074	0.524	4.598

Based on these values the convergence radii of pressure and frictional forces can be calculated according to ITTC guidelines (ITTC, 2002). They are −0.03 for the frictional resistance and 0.53 for the pressure resistance. Therefore it can be stated that even though the total resistance seems not to converge yet, the individual components do converge. This is a well known effect.

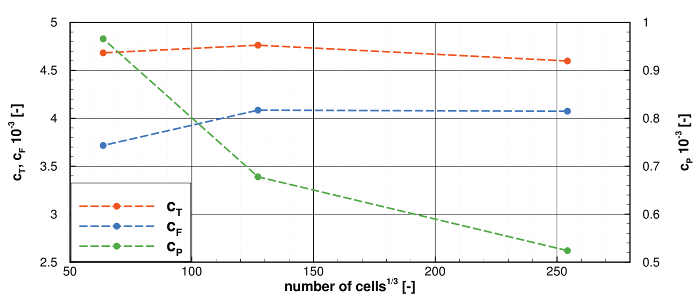

Fig. 4 Grid dependence analysis

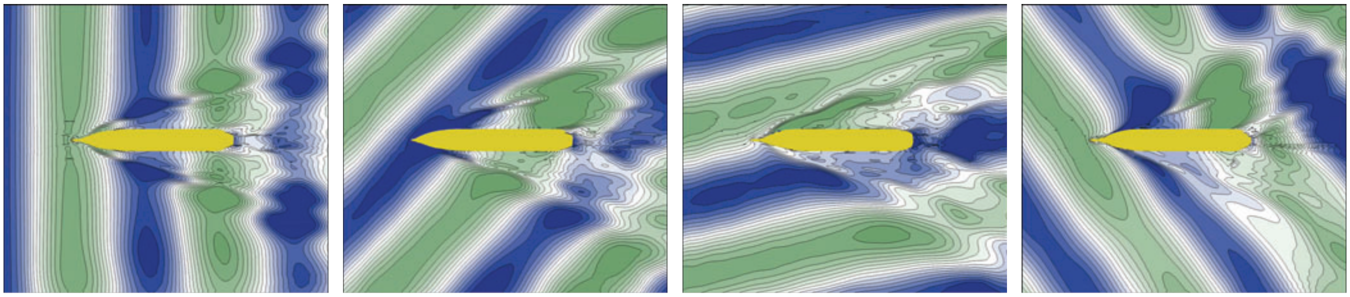

Fig. 5 Waves from different directions

As shown in figure 4 it is explained by the opposite convergence behaviour of friction and pressure forces. The measured calm water resistance from model tests performed at the TUB is 5.87 N, which leads to a c_T of $4.806 \cdot 10^{-3}$. Additional data from HSVA model tests are available which showed c_T of $4.789 \cdot 10^{-3}$. The discrepancy between measured and calculated calm water resistance is less than 5% for all three considered grids.

Harmonic waves For the unsteady calculations in waves a time step of 0.002 made non dimensional with the ship speed and length and ten SIMPLE iterations were used to ensure a good quality of the wave. The quality of the generated waves was investigated for various parameters before in an empty domain and checked for every calculation. The average calculation time per considered case was about two weeks for ten periods on a PC using a single core.

Figure 5 shows snapshots of the performed simulations for various encountering angles. As can be seen even for oblique and following waves a good quality was achieved.

A representative time series plot of a calculated force can be seen in figure 6. For calculating the mean force, the first three periods were ignored, since the wave has not been fully developed yet. When taking a closer look at the time series plot, a small low frequency oscillation can be identified corresponding approximately to the frequency of a standing wave with the same length as the numerical domain. This is due to a slight reflection of the wave at the outlets of the numerical domain, which – despite the damping zones – cannot be completely avoided. Thus it is important to average over a whole period in order to capture the relatively small added resistance correctly. For checking the convergence of the mean forces, the moving average is calculated as well.
The mean forces in waves with forward speed have been compared with results of computations performed with GL RANKINE, a linear potential panel code which allows the calculation of mean values of second order forces through proven approximations widely used in seakeeping methods, see for instance Faltinsen (1990). Figure 7 shows a good agreement between the non dimensional forces and yaw moment from the RANS and panel code for the wave lenght $\lambda' = \lambda/L = 1$. Even for the very small longitudinal force the traces are similar.

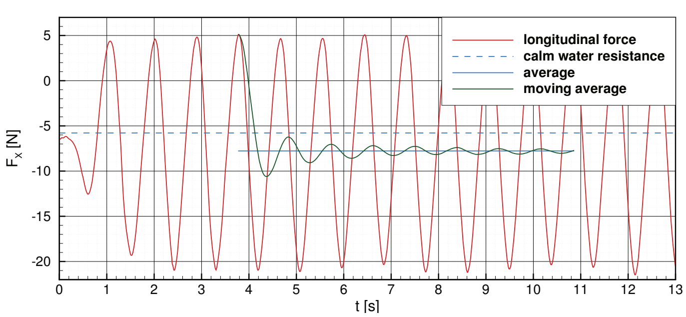

Fig. 6 Longitudinal force, $\lambda' = 1$, $\alpha = 0°$, $\hat{\zeta}_w/L = 0.01$

MODELLING OF MEAN FORCES

After the mean forces have been acquired for all encountering angles ranging from 0° to 180° and wave lengths ranging from 0.75 to 1.5 L, it is possible to proceed with their modelling. Mean forces and moments are made non dimensional as follows:

$$F' = \frac{F}{\rho g L \zeta^2} \qquad M' = \frac{M}{\rho g L^2 \zeta^2} \tag{5}$$

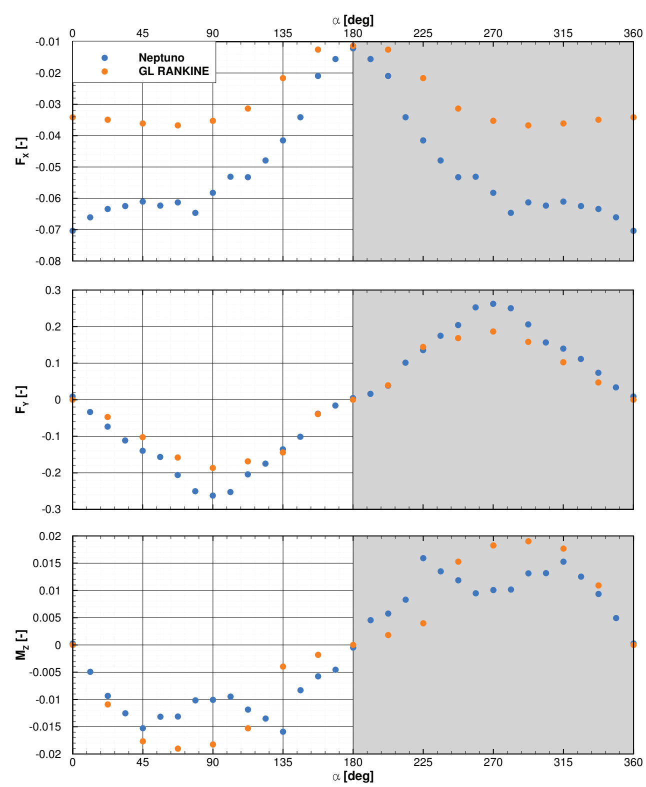

Fig. 7 Comparison with results from GL RANKINE for $\lambda' = 1$ and all encountering angles

The mathematical model described here uses the fact that the dependence of mean forces and moments on the encountering angle is periodical, the period being 360°. Therefore after mirroring the calculated values at 180° – the longitudinal force is axis symmetric, whereas the side force and yaw moment are point symmetric – a Fourier series expansion can be chosen as an approach to model the angular dependence:

$$F = \frac{a_0}{2} + \sum_{n=1}^{6} \{a_n \cdot \cos(n\alpha) + b_n \cdot \sin(n\alpha)\} \tag{6}$$

The Fourier series contains terms up to sixth order and is capable of capturing the angular dependence very accurately for each considered wave length, see figure 8. It should be noted that some of the coefficients are zero and do not need to be considered in the mathematical model. This is due to the axis-symmetry / point-symmetry of the traces regarding $\alpha = 180°$. Just 7 a_n coefficients are needed for F_x and 6 b_n coefficients for F_y and M_z.

To model the dependence of the forces on the wave length λ, the Fourier coefficients are now assumed to be dependent on the wave length:

$$F = \frac{a_0}{2} + \sum_{n=1}^{6} \{a_n(\lambda) \cdot \cos(n\alpha) + b_n(\lambda) \cdot \sin(n\alpha)\} \tag{7}$$

The dependence on the wave length is then approximated by means of a polynomial approach containing terms up to third order:

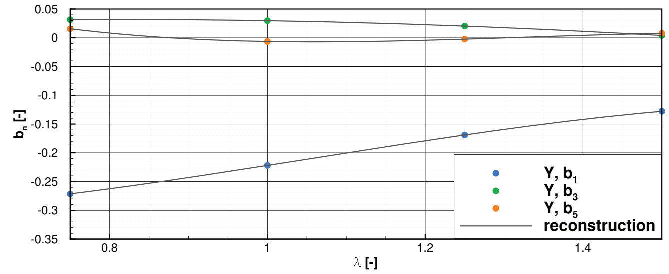

Fig. 9 Polynomial approximation of Fourier coefficients for side force (only non zero coefficients shown)

$$\begin{aligned} a_n(\lambda) &= a_{n3} \cdot \lambda^3 + a_{n2} \cdot \lambda^2 + a_{n1} \cdot \lambda + a_{n0} = \sum_{i=0}^{3} a_{ni} \cdot \lambda^i \\ b_n(\lambda) &= b_{n3} \cdot \lambda^3 + b_{n2} \cdot \lambda^2 + b_{n1} \cdot \lambda + b_{n0} = \sum_{i=0}^{3} b_{ni} \cdot \lambda^i \end{aligned} \tag{8}$$

The quality of this approximation can be seen in figure 9.

For this procedure, the encountering angle dependent Fourier coefficients for at least four wave lengths need to be known, which leads in our case to a virtual test matrix consisting of $9 \cdot 4 = 36$ cases.

The determined coefficients for various ship speeds are then stored in a database. The manoeuvring simulation program reads the calm water hydrodynamic coefficients as well as this wave force database and calculates the mean forces and moments due to waves for the current situation in every time step. These forces are then added to the right hand sides of the motion equations of the ship in order to predict manoeuvres in a single harmonic wave.

Note that this procedure can be extended without the need of new computations to the case of a seaway, not necessarily long crested, by superposing the mean wave forces of the individual wave components according to a given energy spectrum, see for example Faltinsen (1990).

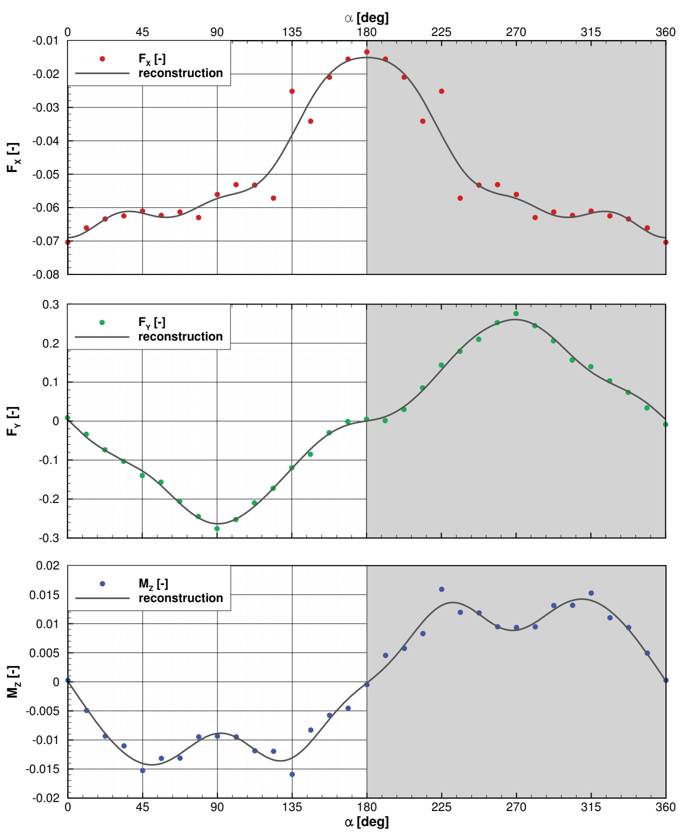

Fig. 8 Fourier series modelling for one wave length ($\lambda' = 1$)

CHECK OF THE MATHEMATICAL MODEL

Figure 10 shows the reconstruction of all calculated forces based solely on the mathematical model. In contrast to figure 8 there are no individual Fourier coefficients used in this case but just the 76 coefficients a_{ni} and b_{ni} from equation (8) which are not zero.

To check if the model is able to predict the forces for situations that have not been used as input for the database, additional calculations for two waves have been performed. The resulting forces for a wave with $\lambda' = 0.85$ and $\alpha = 30°$ are:

	calculation	math. model	difference
F_X	-1.77	-1.81	2%
F_Y	-2.79	-3.01	8%
M_Z	-0.82	-0.94	13%

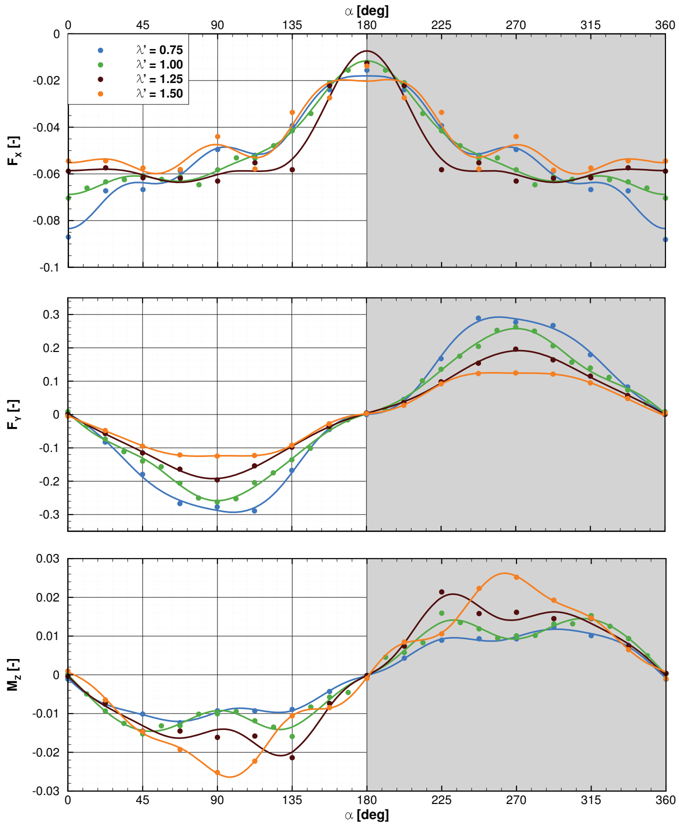

Fig. 10 Reconstruction of all calculated values (RANS) solely based on the mathematical model

A wave with $\lambda' = 1.1$ and $\alpha = 55°$ yields:

	calculation	math. model	difference
F_X	-1.81	-1.76	3%
F_Y	-4.61	-4.23	9%
M_Z	-1.26	-1.27	1%

As can bee seen the discrepancies are acceptably small. It should be noted that this model is intended to serve as an interpolation method. It would not work beyond the range of wavelength used for determining the coefficients.

CONCLUDING REMARKS

In the present paper a mathematical model for approximating mean forces and moments due to waves has been proposed, based on a double parametric approach on the encountering angle α and the wave length λ. The coefficients of the model were entirely determined by means of RANS computations. The model was applied to a twin screw passenger ship. Additional computations, for different cases than those performed to obtain the coefficients have been performed to check the validity of the approach.

The presented mathematical model is capable of predicting well the mean forces and moments for the test case considered. The obtained database containing the coefficients of the model allows an easy implementation of second order wave effects into existing manoeuvring simulation programs.

At the current point the influence of the ship speed (u) and therefore of the encountering frequency is being investigated. Additional coupling terms taking into account the interaction between drift velocity (v) and mean wave forces might also be relevant for manoeuvring predictions and will be checked in future.

The mathematical model should not only capture the effects of diffraction but also radiation forces. Thus, calculations without constraints on the ship motions, especially for the freely pitching and heaving ship, are being performed at the moment in order to determine the wave dependent coefficients of the mathematical model taking into account both effects.

Once these calculations are completed it is straightforward to implement the mathematical model into an existing manoeuvring simulation program and to predict rudder manoeuvres for the considered ship in waves, e.g. a turning circle, a man over board manoeuvre or just a certain change of course, as long as the encountering frequency does not become too small.

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